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ASD TECHNICAL REPORT 61-166

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WEIGHTLESSNESS AND PERFORMANCE
A REVIEW OF THE LITERATURE

Lt. J. P. Loftus, USAF
Lois Reel Hammer

Behavioral Sciences Laboratory
Aerospace Medical Laboratory

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AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
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Project No. 7184
Task No. 71585

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1,600 – August 1961 – 35-1240

FOREWORD

This report represents one phase of a research effort to develop engineering design criteria for manned systems in the zero-g environment. It was prepared by the Crew Stations Section, Human Engineering Branch, Behavioral Sciences Laboratory, Aerospace Medical Laboratory, under Project No. 7184, "Human Performance in Advanced Systems," Task No. 71585, "Design Criteria for Crew Stations in Advanced Systems," and grew out of an annotated bibliography compiled initially by Dr. Melvin J. Warrick, Human Engineering Branch. Literature survey was completed in April 1961.

The writers wish to acknowledge the help given by many librarians, particularly Mrs. Edna Miller, Aerospace Medical Laboratory, in finding the publications reviewed and by those persons who read and criticized the early drafts of the manuscript.

ABSTRACT

The implications of weightlessness as encountered in space flight are discussed, and the known research dealing with the psychological and physiological effects of zero gravity is critically reviewed. Topics are grouped under the headings of orientation, psychomotor performance, and physiological functions, with a special section on methods of research. The major problem area indicated is the effect of weightlessness on gravity oriented sensory mechanisms, particularly the vestibular apparatus, and consequently on both physiological functions and psychomotor performance. An extensive bibliography is included.

PUBLICATION REVIEW

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WEIGHTLESSNESS AND PERFORMANCE
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INTRODUCTION

After World War II, when progress in space technology made it clear that manned space flight could be achieved, various writers began to speculate on the impact of weightlessness upon the well-being of an earth gravity-adapted organism. The focus was upon the unusual physical stimuli of zero g and possible disorientation or confusion caused by the unfamiliar or perhaps conflicting sensations. The outlook was seldom optimistic.

The so-called gravity sense is not limited to one sense modality. Muscle tension present when the skeletal muscles support the body, stimulation of the labyrinthine hair cells by the otoliths, pressure and tactile sensations from the object of support, and the weight of the limbs and internal organs are all means of sensing the direction of the gravity vector (ref. 99), or, more accurately, stress resulting from gravity (ref. 83); and all are thought to be important cues to orientation. Gerathewohl and Stallings (ref. 35) have pointed out that there need not be a conscious percept of gravity if a mechanism exists for maintaining the body in its usual upright position, or orienting itself to the upright. The labyrinthine and posture reflexes normally serve this function. Nearly all the early writers were concerned with the failure of these mechanisms under zero gravity resulting principally from the absence or conflict of sensations from the otoliths, and ensuing conscious disorientation. Confusion from a conscious sensation of falling was also predicted (ref. 22), because the physical stimuli of zero gravity would be those to which the organism is briefly subject in a state of free fall.

The possibility of weakness following changes in muscle tonus and relaxation of reflex tension in the supporting muscles and of incoordination in voluntary movements because of changed energy requirements was also considered (refs. 22, 50, 111). The effectiveness of man as an operator of a space vehicle depends upon his motor as well as his perceptual behavior, making psychomotor performance an important area of consideration.

Less a sensory problem, but equally vital, are changed physical conditions that affect changes in the more mechanically sensitive functions of the body, such as the circulatory system, that are known to be affected by increased gravity. Loss of hydrostatic pressure because of the blood's lack of weight may impair blood circulation (refs. 56, 62, 111, 112). Indeed, this has been the most critical problem anticipated by many writers. Even if adjustment to weightlessness is possible, the probability of survival upon reentry may be lowered.

Many experiments have since been carried out attempting to verify such predictions as these or to prove them groundless. Problem areas have been outlined according to the changed gravireceptor input and the types of behavior mediated by these sense organs, as well as physiological functions that might be affected by zero gravity. While only a beginning has been made in serious weightlessness research, future study will probably follow the lines laid out by the early theoretical analyses.

The approaches taken in the previous literature have determined the point of view of the present report. While the effects of weightlessness could be considered from the customary physiological and psychological standpoints, a distinction between the two disciplines was found to be arbitrary in many cases. This review will, therefore, direct attention toward the changed input to the sensory receptors when $g = 0$ and the consequent changes in specific functions of the organism.

The difficulties in producing weightless conditions for experimental purposes often introduce artifacts attributable to the method of study rather than the variables under investigation. Hence our discussion of the experiments is preceded by a brief review of methods that have been used, so that the results may be evaluated more fairly.

METHODS OF STUDY

The gravitational pull of the earth upon a body is proportional to the mass of the body and is inversely related to the body's distance from the earth. As a result, the rate of acceleration due to gravity is the same for all bodies in any particular location. When a body is not allowed to fall its mass is evidenced by its weight. If a container with a few objects within it is in free fall in a vacuum, the objects will possess all the properties attributable to mass but will appear to weigh nothing. That is, the objects will resist accelerations and acquire momentum if accelerated, but if not accelerated will register zero weight on a spring scale. Two objects of different mass will indicate zero difference on a balance. This occurs because all measurements of weight depend upon opposition to the action of gravity; in a free fall state the force of gravity is unopposed.

Objects in orbit are in a continuous free fall in a vacuum and because weight cannot be measured normally in this environment it is termed "weightlessness." Objects remain in circular orbit when their forward velocity is such that as they fall they never come closer to the surface of the earth.

Since a force applied to an object results in its acceleration, forces are measured in units of acceleration of a reference mass, often using g (32.16 ft/sec^2), the normal acceleration due to earth's gravity, as a unit. The condition of free fall is termed zero g, since a three-axis accelerometer in orbit would indicate zero forces, unless a rocket engine were in use to change either velocity or attitude. Ritter and Gerathewohl (ref. 83) argue forcefully that, for clarity, the terms "zero g" or "null g" should be used to describe the physical state and the term "weightlessness" be reserved for the physiological and psychological experience of the state. The authors of this paper have followed this convention.

Zero g can be produced by allowing a body to free fall and it can be simulated in the horizontal plane by eliminating friction so that bodies act and react in a purely inertial manner. Weightlessness can be partially simulated by immersing a body in water. All three techniques have been used to study the effects of zero g and each is subject to certain theoretical and practical difficulties that should be noted if data are to be realistically evaluated.

The discussion which follows describes the principles used in various experimental devices and techniques and some of the theoretical and practical limitations met in applying them. A more detailed description of the basic principles may be found in Haber (ref. 49) and Haber and Gerathewohl (ref. 50), while Haber (ref. 47), Haber and Haber (ref. 48), Gerathewohl, Ritter, and Stallings (ref. 34), Gerathewohl (ref. 33), and Ward (ref. 117) have developed several nomographs and simplified methods of calculation to determine attainable periods of weightlessness.

Ballistic Devices*

Zero g is only obtained in the condition of free fall when the object is uniformly accelerating at 32.16 ft/sec^2. Consequently devices which produce periods of zero g are classified by the manner in which they produce acceleration and are judged as to the precision with which they control acceleration. In order of increasing complexity these devices are drop towers, elevators, sleds, aircraft, and ballistic missiles. All use the same basic kinematics.

The drop tower uses the simplest application of the principle. The test object is accelerated by the force of gravity and zero g is achieved by removing all external forces which oppose this acceleration. The major source of opposition is aerodynamic drag, which has an appreciable effect within a fraction of a second. Although it is impractical to create a vacuum within a drop tower shaft of significant length, short periods of zero g can be achieved using the basic principle. A large, aerodynamically efficient capsule within which the test package free falls in a vacuum can be dropped in an enclosed area free of atmospheric turbulence. The interior dimensions of the capsule and its aerodynamic efficiency fix the time period available. Norair Corporation has designed such a facility in which 2.2 seconds of zero g are produced.

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*The basic relationship between the period of zero g produced and the space required is indicated in the following formulae. These formulae indicate the period theoretically available; practical difficulties will always reduce the time values derived.

In all cases V_e is initial velocity, t is time at zero g, g is the acceleration due to gravity (32.16 ft/sec^2) and θ is the angle at which the initial velocity is applied.

For the drop tower $t = 2h/g$ and $h = 1/2\, gt^2$
For the elevator $t = 2\, V_e/(1-n)g$ and $h = V_e^2/2(1-n)g$
For the missile or aircraft $t = 2\, V_e \text{Sin}\, \theta\, /(1-n)g$ and $h = V_e^2 \text{Sin}^2\theta\, /2(1-n)g$

The obvious advantage of the drop tower is its potential simplicity and availability; practical problems, such as capsule size and deceleration problems, will probably limit the zero-g period available to a maximum of 5 seconds and prohibit biological studies. However, this is an adequate period for the study of fluid dynamics and other physical phenomena which can be studied in scale models, since within the constraints mentioned this method produces very exact states of zero g.

The elevator is a natural progression from the drop tower. The driving unit can counteract drag forces, relieving the restriction on test package size, and the effective shaft length can be increased by accelerating the cabin upward initially. The system is economical since it can be designed to cycle repetitively.

In practice, however, the driving units of elevator systems are not capable of precise control of acceleration over any extended distance and consequently those used provide only short intervals of zero g (one to one and one-half seconds). These units, however, are useful for the environmental test of missile components and other problems which can be accomplished in short time periods and are not contaminated by the intervening periods of high acceleration.

A missile, sled, or aircraft moving along a properly calculated trajectory performs in exactly the same manner in the vertical axis as does the elevator, only now a horizontal velocity is added. The absolute value of this horizontal velocity is determined by the control requirements of the vehicle in question. For example, in aircraft the minimum acceptable horizontal velocity is the normal stall speed to insure positive aerodynamic control. The aircraft would not stall while weightless, stalls being a function of weight, but this speed governs the effectiveness of the control surfaces which are used in the course of the maneuver.

The horizontal velocity component is introduced at the cost of some efficiency in maneuver configuration to provide efficient application of power and control. Even with increased freedom of control the theoretically available periods of zero g are not routinely achieved in practice. Difficulties in the precise control of acceleration in all three axes, compounded by the extraneous accelerations introduced by atmospheric turbulence, degrade the theoretical performance of aircraft and low altitude missile shots. Longer range missile shots are infrequent and place rigorous size and weight restrictions on experimental packages. While sleds have been widely discussed, no one has built a facility of this type.

In practice, aircraft routinely provide 10- to 20-second periods of precise zero g when executing trajectories with a theoretical capability of 35 seconds. As more extended trajectories are attempted there is increased difficulty in control of acceleration in all three axes and consequently either a general degradation in performance or no increase in the duration of satisfactory zero g within the longer trajectory.

While aircraft offer a practical method of producing short periods of zero g, they also introduce a number of uncontrolled variables into the experimental situation. Vibration, noise, reduced pressure, and sometimes other distractions are present during the maneuver and high accelerations are required at either one or both ends of the trajectory. The interaction of these environmental variables and the relatively long time required for many human and animal physiological systems, particularly the cardiovascular system, to adapt to changed conditions may directly contaminate physiological measures and indirectly performance measures. Subject selection may eliminate the grossest effect of these extraneous variables but no really satisfactory method for controlling them seems to be available.

Frictionless Devices

The outstanding mechanical characteristic of zero g, the inertial movement of bodies, can be obtained in the horizontal plane in the presence of gravity if all frictional forces can be eliminated. A number of studies have used this simulation technique and two methods of eliminating friction have been used. In one case, graphite lubricated bearings were used but friction has more commonly been reduced through the use of "air bearings."

Air-bearing devices use the air cushion created by the flow of pressurized air between two polished surfaces to provide very low friction contact, yielding minimum values in both stiction and sliding friction. Friction seems to be effectively zero for the relatively large masses and forces usually involved in the use of such devices.

The air-bearing platform offers a highly economical method for studying many aspects of human motor performance and determining equipment design characteristics. Two cautions, however, must be exercised in judging the data obtained using such devices. All the inertial effects of forces exerted in a particular action will be reflected into the plane of free motion, and are not necessarily the true reactions that would take place if all axes of movement were equally free. Secondly, the gravity vector is present in the system as a component force and as a variable acting upon the operator. The effect of gravity on the neuromuscular system is not specified, but is deduced from the normal muscular tone required to function in the upright position in opposition to the gravity vector. This effect should not change on the air-bearing device

Immersion Devices

Immersion devices are used to provide a physiological equivalent of the zero-g condition. A body suspended in a fluid of approximately the same density is subjected to equal pressure at all points and its weight is largely supported by the fluid. Since this condition diminishes many of the gravity cues and reduces the workload of the cardiovascular system, it is logically similar in many ways to the condition of the body while weightless (refs. 60, 73).

The effectiveness of the simulation depends in part upon the degree to which the gravity cues are eliminated and in part upon the reduction in the physical energy requirements of the body. Since the gravity vector is sensed by the vestibular otoliths and shifting weight of the viscera and differential density of the limbs when the subject moves, as well as by pressure from the supporting surface and tension in the supporting muscles, the simulation is imperfect and inadequate. The reduction in the physical energy requirements of the passive physiological system, however, is unquestioned and offers the opportunity to observe function of these systems under a prolonged condition of reduced demand, a condition Hartmann et al.(ref. 52) have termed a hypodynamic environment.

Levine (ref. 65) has proposed that the subject be submerged within a tank and rotated about his longitudinal axis, parallel to the surface of the earth. High rates of rotation, in excess of the response capability of the otolith mechanism, would then eliminate these gravity cues. The technique has some logical merit and would improve many characteristics of the simulation, but it also creates a number of significant artifacts. In addition to the necessary immobility of the subject in such an environment, the influence of physical isolation, dangers from failure of the breathing system, and artifacts due to Coriolis forces when the subject moves his limbs out of the axis of rotation may vitiate the advantages of the method.

The great advantage of immersion simulation is the long periods that can be observed; however, the exact applicability of the observations seems open to some question. It does not appear likely that man's role in space will be as passive as the resting state of subjects in immersion studies. Yet, the potential hazards of reduction in acceleration stress tolerance are too great to ignore the data obtained with this technique. It is of unquestioned value in estimating the physiological effects of zero g, and though the artificial nature of the method offers little opportunity to study motor performance, many studies of mental and perceptual processes are feasible.

At present the methods available for producing zero g for the study of human and animal performance provide too brief an interval to allow effective study of all the processes of interest in human and animal performance, although they are adequate for the study of a great many physical problems. The simulation methods which allow prolonged observation possess a certain logical validity but have not been demonstrated to be effectively equivalent. Points of deviation from the weightless state are not easily determined solely by logical analysis. Very little information is available from the limited number of orbital and suborbital missile shots that have carried biological experiments, but the available data do coincide with the observations in experimental environments.

ORIENTATION

Orientation is accomplished by the interaction of a number of senses— vision, the vestibular apparatus, and the kinesthetic sense. Sensations from all of these receptors help inform us of our relation to our surroundings.

Campbell (ref. 10) offers the following definition, which appears consistent with the meaning intended by other writers:

> " . . . . objective orientation is awareness of position relative to other objects, the most important of which is the earth. The most important reference point is the center of the earth. Orientation with respect to the center of the earth is entirely gravity-based." (ref. 10, p. 63)

Because of the importance of the gravireceptors in maintaining orientation, it has been thought that an absence of gravity would result in varying degrees of disorientation, particularly with respect to up and down, which would cease to have meaning in an objective sense. Of Campbell's "orientation triad"——visual, vestibular, and kinesthetic senses—vision is not a gravireceptor and should not be directly influenced by zero gravity. Strughold (refs. 101, 103), Gauer and Haber (ref. 22), Campbell (ref. 10), and Balakhovskii (ref. 1) have predicted that orientation in the weightless state would be possible only if one has the aid of vision. Indeed, Beritov (ref. 3) has found that deaf persons without functioning labyrinths cannot orient themselves with eyes closed, although they can learn to perform directed movements without vision.

The sense of touch, though seldom mentioned in the literature, also may be valuable in orientation with respect to near objects. While Strughold discusses in more detail the pressure sensations of the skin, which are not necessarily lacking under zero g, he also suggests that exclusively visual orientation may be possible. This suggestion is advanced on the basis of experiments in which fish were found to swim toward a light source, whether above or below the aquarium (ref. 101).

Research into orientation in a weightless state has taken several directions. The most direct is a phenomenalogical approach. human subjects are exposed to zero g and then asked to describe their experiences, particularly any difficulties in orientation. Some attempt has also been made to determine the sensitivity of the vestibular sense and its contribution to orientation. Still further investigations have aimed at specifying the deviations from normal vision that are known to occur with changes in acceleration fields.

Experience of Human Subjects

As far as could be determined, von Diringshofen (refs. 111, 112) was the first to study the experience of weightlessness in flight. This state was achieved by a vertical dive in a powered aircraft. On the basis of his experience, von Diringshofen recommended the use of shoulder harness and seat belts, supplying the pressure sensations discussed by Strughold (ref. 103).

Research in weightlessness with human subjects began about 1951 in the United States. Gerathewohl (refs. 25, 26) relates the initial experiences of Scott Crossfield and Major Charles Yeager, test pilots who flew parabolic trajectories in jet fighters. The former reported a feeling of "befuddlement" during the transition to zero g that lasted until after the fifth flight. He felt no sensation of falling, thought by Gauer and Haber (ref. 22) to be a necessary condition of weightlessness, but Major Yeager did, as well as disturbance in orientation that passed when he pulled out of the parabola.

About the same time, Ballinger (ref. 2) exposed a number of subjects to weightlessness inflight. They maintained their sense of orientation while being held in the seat and having a visual reference point. The widely quoted speculation that "had they been unrestrained and blindfolded, disorientation might have been extreme," appears to have received too much attention.

Gerathewohl (refs. 27, 28) documented the experiences of 16 zero-g subjects. Several, but no means all of these, did report disorientation with eyes closed. Schock (ref. 88) tested 10 subjects wearing dark hoods that excluded vision. None felt a falling sensation but did indicate that only the pressure of the seat belt enabled them to distinguish "up" from "down."

Many flight tests conducted since 1959 by the Aerospace Medical Laboratory show that subjects are able to adjust to weightlessness quickly (ref. 125). A cargo aircraft was used as a laboratory, providing ample room in which unrestrained subjects could float about free of a surface. Orientation appeared to be based on visual cues, but while some persons accepted the vehicle structure as a frame of reference, others oriented to their own bodies. However, tumbling exercises can produce disorientation and vertigo after several revolutions (ref. 4). Rapid recovery from vertigo occurred when motion stopped.

That vertical reorientation is possible has been shown in Simons' (ref. 96) experiments on walking behavior under zero g, in the same aircraft. The ceiling of the aircraft cabin was used as a walkway. All subjects who participated in this experiment reported an immediate and effective reorientation, with the surface on which their feet were planted perceived as "down." Interestingly, this orientation is based on tactile

sensations that would normally be in direct conflict with the visual cues. This observation may prove to be highly significant for our understanding of orientation, and may refute the frequently expressed notion that a space compartment must contain an abundance of visual cues to up and down directions in the customary sense (ref. 29). On the contrary, Simons proposes that the egocentric orientation observed in his subjects may make it possible for a crew compartment to have several "floors" determined by the positions of the respective crew members.

Vestibular Sensitivity

Some efforts to determine the threshold of sensitivity for the otoliths have used water immersion techniques. The assumption underlying this technique is that the specific gravity of the body approximates that of water closely enough that immersion reduces or equalizes differential cues of muscular tension, hydrostatic pressures, and pressure and tactile sensations arising from the object of support. If artifacts can be eliminated, sensitivity of the otoliths can be studied in relative isolation from the other gravity senses.

Even before weightlessness was an important consideration, Garten (ref. 21) made use of the immersion method to study vestibular functions. Subjects placed in a tilting chair under water were much more variable in judgments of position than on land. Other studies have investigated relative sensitivity to various positions of the body as well as response to change in position. Awareness of body position and perception of the vertical have been used as performance measures, giving information about orientation in a simulated weightless state.

Because Quix (ref. 81) reported the presence of an otolithic "blind spot" when the head is hanging down with the body supine, it has been thought that immersion of the subject in such a position should approximate physiological weightlessness. Knight (ref. 60) attempted to validate this method of simulation by testing perception of changes in position about a horizontal axis. His results did not verify the "blind spot," but, while upside down, his subjects could be tilted through large angles before a change in position was reported. He concluded that the simulation, while imperfect, might still be useful.

Brown (ref. 5) studied the effects of rotation under water on perception of the vertical. Using divers in a submarine escape training tower, he found that at depths approximating neutral buoyancy for the body (18 to 25 ft), determinations of vertical were poorest when the subject's head was down or tilted back. Movements of the head appeared to assist determination of the vertical. The greater density of the lower limbs also provided cues to the vertical when the subject released himself from the bar used to rotate him and swam to the surface.

Margaria (ref. 73) studied the perception of static position with reference to the vertical. He found that performance improved rapidly with practice, that the variability was largest when the subject was inverted, but that performance on land did not differ significantly from that in water. He presented the results as a demonstration that the direction of gravity is sensed more accurately by the otoliths than by other mechanical receptors, yet he concluded that only minor functional changes would result from total absence of otolithic stimulation during weightlessness.

Schock (ref. 88) tilted subjects from the vertical and then measured their accuracy in judging when they had been returned to the vertical. Errors ranged from zero to fifteen degrees, and both intra- and intersubject variability were large.

Schock (ref. 88, 90) also tested perception of the visual vertical under water by having subjects adjust a lighted bar to an apparently vertical position. A marked decrement in accuracy was found in water compared to adjustments on land. The decrement was generally larger when the head or whole body was tilted than when the subject was seated normally, both on land and in water.

Mann (ref. 70) has reviewed most of the earlier studies in spatial orientation and reports considerable variation in both mean errors and variability. Many of the differences in results appear to be due to varied experimental procedures and conditions. The same remarks no doubt apply to the experiments discussed here.

Despite the potential usefulness of the water immersion technique, available reports do not furnish exact and complete information on the sensitivity of the gravireceptors. Authors disagree on the relative importance of the kinesthetic and vestibular sensors. Methodological problems and differences in procedure may account for part of the disagreement in both hypotheses and results. No one study has yet been extensive and thorough enough to resolve these difficulties.

A special psychophysical problem regarding vestibular sense in a reduced gravity environment has been discussed by Gauer and Haber (ref. 22) and Haber and Gerathewohl (ref. 50). The logarithmic relation between stimulus and sensation described by the Weber-Fechner law can be interpreted to mean that in an environment of less than the 1 g, small variations in acceleration might yield disproportionately large changes in sensations. This is based on the presumption that the sensory zero is 1 g since this is the normal environment of the organs.

In later papers, Gerathewohl (refs. 24, 25) discounts the importance of this effect on several points: the Weber-Fechner law is only an approximation; it does not represent the true relationship at the extremes of the perceptual scale; the difficulty in identifying and measuring the variables makes interpretation difficult; and, finally, the experiences of subjects to date did not seem to support the prediction. Gougerot (ref. 39) also criticized this interpretation of the Weber-Fechner law as being in conflict with the principles of nerve physiology and cites examples of illusory phenomena as evidence of the conflict.

The interest occasioned by this speculation highlights our inadequate understanding of basic psychophysical phenomena. Our conceptualizations have failed to predict the actual relations at the extremes of the sensory continua, owing in part to the practical difficulties that have hampered data gathering in these ranges. The reduced gravity environment will offer a unique opportunity to investigate within the lower ranges a number of sensory phenomena that are influenced by gravity.

Animal Vestibular Functions

Experiments on animal subjects during zero g have helped to clarify the roles of all three orientation senses—visual, vestibular, and kinesthetic. Animal experiments permit a wider range of organic conditions and more precise experimental control than studies of human behavior. However, unless a clearly defined response is being observed, one must beware of anthropomorphic assumptions in the terms used to describe animal behavior and in the interpretations placed upon it. Limitations are also imposed by unknown effects on behavior of the general conditions of flight, (noise, altitude, vibration), imperfect conditions of zero g and the consequent extraneous accelerations, and different responses to these conditions by "normal" and experimental animals.

Henry et al. (ref. 53) have reported tests in four V-2 and three Aerobee rockets carrying mice and monkeys. By means of photographic records, normal mice were compared with labyrinthectomized mice traveling in the same rotating, smooth walled drum. Uncoordinated or disoriented behavior was observed only in normal animals or in those not provided with a foothold. During weightlessness there was no apparent disturbance or behavior in the labyrinthectomized animals, which could not receive "abnormal" or unusual vestibular sensations. When there was a small shelf on the wall of the rotating drum, a normal animal clung to this. Otherwise the normal animal clawed or floated aimlessly or gave other evidence of disorientation. Here again is evidence suggesting that changed vestibular sensations under zero-g conditions can produce disorientation, but that body control is possible with vision and the tactile sense. Complete zero g probably did not prevail, for the role and pitch of the rocket during the free fall phase produced acceleration of about 1/20 g. Simons (ref. 95) suggested this may have been sufficient to aid orientation. On the other hand, these fluctuations may have been the cause of the disorientation.

A more objective description of an animal's behavior is possible from the experiment conducted by von Beckh (ref. 106) using South American water turtles, since a test was made of a specific, previously observed reaction that depended on the animal's orientation. These turtles are described as being very skillful at striking at bait, and their three-dimensional coordination in water made them interesting experimental animals.

One turtle had suffered an apparently permanent injury to its labyrinths and was found to be at a severe disadvantage. After a time it began to orient itself by means of vision, as shown by its failure to right itself normally when its eyes were covered with a hood. This animal and three normal ones were exposed to subgravity in a vertical airplane dive, and their bait striking behavior compared under this condition. Only the turtle without labyrinthine functions, but visually adapted, reacted normally when presented with food; the others' actions were ineffective in striking at the bait. As might be expected, the normal animals' adaptation to subgravity paralleled the previous adaptation of the animal with labyrinthine injury, although 20 to 30 flights were not sufficient for them to reach an equivalent skill. It should be pointed out that complete adaptation after the injury required about three weeks.

Other writers have demonstrated the failure of normal labyrinthine functions during weightlessness by observations of the well known righting reflex in cats. This response is triggered by otolithic stimulation when the cat falls or is dropped; first the head and then the body will turn so that the animal lands on its feet.

Gerathewohl and Stallings (ref. 35) found that, in general, the righting reflex occurred if the animal was relased immediately after becoming weightless, but was delayed or failed to occur at all if the animal was held during about 20 seconds of zero g before being released. Since the head turning and righting reflexes may occur in labyrinthectomized cats with the aid of vision (ref. 59), the subjects in Gerathewohl and Stallings' experiment were hooded during some trials to control the visual righting reflex. The results did not differ substantially from those of the other trials. The results of the experiment were attributed to "the changed stimulus pattern of discrepant gravitational, visual, and tactile cues which caused spatial disorientation," (refs. 35, p 354). The authors concluded that the specific otolithic stimulus is not acceleration, but change in acceleration.

In another study, Schock (refs. 88, 91) observed the lift reaction, and the toe spread and springing postural reflexes as well as the labyrinthine righting reflex. The subjects were two normal cats, two with ablations of the vestibular cortical area, and two bi-labyrinthectomized cats (eighth cranial nerve sectioned). The results were consistent with Gerathewohl and Stallings' findings. The normal, unoperated cats performed the righting reflex only if released during the first 5 to 6 seconds of zero g. After a 10- to 15-second exposure, the reflex did not occur. This was found also in the head-righting test, while the other postural reflexes were not seen during weightlessness. Behavior was the same when eyes were covered. A similar loss of the labyrinthine reflexes was observed in the case of cats with cortical ablations, whose responses were normal during straight-and-level flight. However, the experimenter felt that these animals were less "wildly disoriented and confused." The cats without intact vestibular apparatuses did not exhibit any of the reflexes either on the ground or during weightless flight. With eyes open, they did not appear to be disoriented, but with eyes covered, the animals "clawed wildly, scrambled, attempted to remove the hood, and appeared to dislike the sensations immensely" (ref. 91, p 7).

The occurrence in pigeons of another labyrinthine reflex was investigated by King (ref. 58). When a pigeon is held and its body tilted, a compensatory turning of the head to maintain its original orientation takes place, a reflex thought to originate in stimulation of the utricle. The compensatory response was elicited in both normal and decerebrate birds under 1 g in normal flight, but failed to occur in the weightless state. This too was interpreted as evidence that the utricular otoliths do not function normally under zero gravity.

Visual Illusions

Also considered a problem of orientation are certain visual illusions, especially those caused by vestibular stimulation, for they can result in serious confusion or disorientation. Since this is equally true in conventional flight and in space flight, their occurrence and form under conditions of weightlessness deserve attention.

The phenomena that have been of interest are classified as the "oculogravic" illusion. The oculogravic illusion is an apparent movement or displacement of a visual stimulus as an effect of the resultant of acceleration and gravity. When a seated subject undergoes chest-to-back acceleration (i.e., as in an accelerating car or aircraft) he experiences a sensation of tilting backwards. A visual target observed under this circumstance appears to be displaced upwards. The degree of displacement corresponds to the angle between the resultant force and the normal vertical. Deceleration or back-to-chest acceleration causes the displacement to appear downward. The sensory basis is thought to be stimulation of the otoliths in the utricle of the inner ear (ref. 42).

Gerathewohl, in a theoretical discussion of visual phenomena under weightlessness (refs. 23, 24), extrapolating from results obtained under accelerations greater than 1 g, the range in which the phenomenon has been most extensively studied, predicted that in acceleration environments of less than 1 g targets would appear to be displaced downward. Investigating this hypothesis, Schock (refs. 86, 88) describes the occurrence of the illusion during subgravity trajectories in a fighter aircraft. A small luminous target was observed in darkness. The target appeared to move down during increased g, upward upon transition to zero g, and stabilized or oscillated slightly during weightlessness. The oscillations were attributed to occasional slight extraneous accelerations, hence Schock concluded that the illusion may not occur in complete weightlessness.

Gerathewohl and Stallings (ref. 36) have also studied what they, perhaps more accurately, term the oculoagravic illusion. In this case an induced after-image moved downward during acceleration and into the upper half of the visual field upon entering weightlessness; in some instances it continued to move upward, and in others to return to center during the weightless period.

Recently observations have been made by weightless observers floating in a large darkened area with a dimly illuminated disc as the only visual stimulus (ref. 97). Under these conditions subjects report downward movement of the visual stimulus during the high g portion of the maneuver and upward movement on entry to weightlessness. Perception of the relative rotation of the aircraft about the free-floating subject is occasionally reported under these circumstances but not when the visual field is more structured.

The mechanism of these illusions remains obscure. There does appear to be a geometric relation between stimulation of the gravireceptors and the illusory displacement. Yugarov et al. filmed the movements of a rabbit during a rocket flight and conclude that the illusion is caused by displacement of the eyes brought about by reflex stimulation from the otolith apparatus (ref. 124). Such reflex movements do not completely account for the phenomenon since both after images and actual targets are reported as moving in the same direction.

How critical this illusion may be in subgravity environments cannot be decided on the basis of available evidence. Studies to date have failed to describe the illusory movement in sufficient detail to define the strength of the illusion and the acceleration environments have not been specified in the same detail and in precise physical terms in each study. Data from Graybiel and Patterson (ref. 45) indicate that the sensitivity of the sensor may vary depending upon the position of the body relative to the acceleration vector. Witkin and Asch (ref. 122) and others have shown that many other variables such as degree of structure in the visual field, adaptation, and expectancy all interact in the determination of such perceptions The sophistication of the observer and the manner of reporting the observations probab influence the results significantly (ref. 71).

Illusions of Movement

Since Gauer and Haber (ref. 22) predicted that the weightless man must experience a sensation of falling, the sensation of body movement in the absence of gravity is of interest. Reports, however, are meager and not consistent.

Von Diringshofen (ref. 112) reported that there was no sensation of falling, only a feeling of floating between the seat and harness, when zero g is produced in a dive. He points out different sensations accompanying the various means of entering the zero gravity state—forward dive, parabolia flight, and subgravity tower—and proposes that sensations of falling are more likely the steeper the gradient of acceleration during transition (ref. 113).

Gerathewohl (ref. 27) has presented the most complete account of subjective reports. Only 3 of 16 subjects noted positive sensations of movement but several others reported a "feeling" of floating. In another group of 47 subjects, almost all reported a sensation of floating slowly, while some even felt as though they were actively tumbling or rolling (ref. 29).

Pigg (ref. 79) has attempted to record in some detail the extent and duration of illusions of body movement in seated subjects. While the phenomenon appears to be by no means universal, some observers have experienced definite sensations of rotation during weightlessness. The sensations of movement that are noted are probably due to the position of the subject and to extraneous accelerations. Bodily sensations such as these may also be influenced by involuntary relaxation following heavy g loads and changing muscular tension during weightlessness, such as the apnea, increased rigidity of the trunk, and contraction of thoracic musculature reported by Lomanaco et al. (ref. 68).

Conclusions

The possible complexity of the orientation problem for man in space is undetermined. The influence of such variables as training, individual differences, and previously formed associations, and the relative roles of vision and the gravireceptors for orientation are largely unknown.

The manner in which conflicting gravitational and visual stimuli are integrated by the nervous system is a gap in our knowledge that becomes apparent when one tries to predict the importance of the absence of the gravitational vertical and the significance of visual illusions. Nevertheless, the experience of many observers in flight indicates that orientation is little problem during short periods of weightlessness if customary visual or tactile references are present.

The unknown effects of these and other factors may assume more importance for orientation during longer periods of weightlessness. Exact information about both absolute and difference thresholds of the gravireceptors would aid in predicting the effects upon perception of small accelerations. If one adapts to weightlessness as, for example, the eyes adapt to darkness, sensitivity to small stimulus values would be greatly increased, and could greatly affect one's ability to orient either himself or his vehicle when subjected to subsequent accelerations.

PSYCHOMOTOR PERFORMANCE

The problem of motor performance and muscle capability in a weightless environment comprises two factors, not always distinguishable. In addition to a possible decrement due to changes in the musculature or nervous system, such as incoordination or loss of muscle tonus, behavior is affected by the physical limitations of the environment imposed by the changed force fields. The unaccustomed instability of free bodies presents unfamiliar problems in handling objects or moving from one place to another. The former problem is more likely to be a hazard in space travel, while one might expect that the latter could be overcome by training or by restructuring equipment and behavior requirements.

Changes in muscle tonus during weightlessness, occurring because the skeletal muscles no longer need to support the body's weight, have been predicted by several writers (refs. 1, 22, 114). In addition, Haber and Gerathewohl (ref. 50) expected incoordination in movements of the weightless limbs. Because only their inertia must be overcome, less effort than one is accustomed to is required to move the arms or legs, assuming undiminished muscle strength.

Strughold (ref. 103), on the other hand, thought there should be little disturbance in coordination. Control of movements can be achieved by means of vision and the proprioceptors, which sense position and movement of the limbs. As evidence he points to the controlled movements achieved by skilled divers and by cats in free fall, the precise repetition of response that has been experimentally demonstrated in the absence of pressure and muscle tension inputs, and the adaptation to weightlessness shown by numerous subjects. The latter, however, seems to indicate that some experience is required in the weightless state before one's performance becomes skilled.

Animal Studies

Experiments with animals have provided very little information regarding performance capability. Galkin et al. (ref. 20) report on Soviet dogs sent on rocket flights. The only striking observation given was that, according to photographs, dogs were passive during increasing g, but upon entering the weightless phase of the rocket's flight, the dogs' heads abruptly rose above the level of the cradle in which they were restrained. The authors say, "This evidently is the result of the fact that the tonus of the extensor muscles of the neck and back is no longer equal to the gravitational force and the G-stress." The famed dog Laika, placed in orbit in Sputnik II, has, as far as is known, experienced weightlessness the longest of any subject. Kousnetzov (ref. 61) reports that during zero gravity, "Owing to a contraction of the muscles of the limbs the animal made small bounds on the floor. To judge from the recordings, these movements were smooth and of short duration." Because of the limited movement possible by the dogs in their space compartments and the sparsity of information supplied, these reports add little to an evaluation of the effects of weightlessness on motor performance.

Testing a well-trained response, such as that described by Pickering et al. (ref. 78), could be more informative. Monkeys that had learned a shock-avoidance lever-pulling task were tested in weightless flight. It is said, "The resulting movie films have shown that the animals can perform effectively during these periods of weightlessness," (ref. 78, p. 84). Since no performance data are given, we are left in doubt as to the level of effectiveness, especially since the authors continue by suggesting a training program to determine improvement with experience in the weightless state.

Tonic postural reflexes under labyrinthine control apparently are changed when labyrinthine functions are lost (see page 11). Fukuda et al. (ref. 19) found changes in neck muscle tonus corresponding to changes in g-forces to which animals were subjected. Rotation and flexion reflexes resulting from unilateral labyrinthectomy were abolished under weightlessness.

Yazdovskii et al. (ref. 123) observed the "postural reflexes" of white mice and rats during a rocket flight. During the 9 minutes of zero g no evidence of complete adaptation to the environment was obtained. However, after 40 to 45 seconds, the animals' movements were slower, smoother and more coordinated than initially.

Human Psychomotor Experiments

In his first weightless flights, von Diringshofen (ref. 114) noted a sensation of slight uncertainty in commanding coordination of the musculature, which he compared to the previously observed feeling of powerlessness in free fall or dive of an aircraft (ref. 93). This sensation was lost with repetition of the maneuver. When in 1951 Scott Crossfield produced a zero-gravity state in a fighter plane, he reported a tendency to overshoot while reaching for a switch (ref. 25).

To explore these tendencies further, Gerathewohl et al. (ref. 37) conducted an eye-hand coordination test in weightless flight. Subjects thrust at a paper target with a stylus, and their errors were measured. There was a tendency for subjects to cluster hits around the bullseye under normal gravity but to hit the target above the center during zero g and below center during increased g. Some adjustment to the zero-g condition was indicated by a steady reduction in the average upward deviation from the bullseye up to the final (sixth) trial; responses under acceleration did not show such change. Nevertheless, amount of error showed little decrease under any of the three conditions. Their conclusion was that eye-hand coordination is moderately disturbed by weightlessness, but that adaptation is possible.

Somewhat similar are the findings of von Beckh (ref. 106). Subjects attempting to draw crosses in prearranged squares on a sheet of paper showed some inaccuracy under zero g with eyes open, but most striking was the behavior under the same condition but without visual control: crosses that should have been placed in the lower right quarter of the page drifted to the upper right. No such deviation was shown under 1 g with eyes closed, indicating the importance of vision for motor control in the weightless condition. The direction of the error may be reasonably attributed to residual tonus in the abductor muscles.

Schock (ref. 88) reports a modification of von Beckh's experiment. Subjects under subgravity with eyes closed drew the crosses in approximately the right direction, but tended to misplace them outside the boxes. The author felt the errors under subgravity could not be explained by lack of vision alone, although the extent of the error was not given and no statistical tests were mentioned.

The reactions of 20 pilots to zero-g flights were briefly reported by Coe (ref. 15). The action of setting an instrument dial was not impaired but did vary with the subjects' amount of experience as pilots. Again, quantitative results were not given.

Wade (ref. 116) measured times for operating three kinds of switches—pushbutton, toggle, and rotary. Mean response time, i.e., time to perform a complete cycle from pushbutton switch to test switch and return, increased by 15 percent during weightlessness. The three types of response were differentially affected, with an increase of 21 percent in time to operate the toggle switch, 15 percent for the pushbutton, and 9 percent for the rotary switch. Mean operating time for all the switches under 1 g was 0.98 seconds, with the pushbutton having the lowest response time under both one g and zero g. While these differences are statistically significant, the influence of panel arrangement and response compatability were not adequately controlled, and the data cannot be compared between switches.

Lomonaco et al. (ref. 67) and Gurfinkel' et al. (ref. 46) have used elevators produce short periods of zero g rapidly alternating with increased positive g. Lomonaco found increased muscle tonus and a slight but definite motor incoordination in an aiming test, which diminished during several consecutive runs. The performance of deaf subjects without labyrinthine functions was affected to a lesser extent than that of normal subjects.

Lomonaco et al. (ref. 69) studied coordination using a switching task comparable in some ways with that used by Wade. He too found decrements in speed and accuracy. Repetition of the task showed improvement and lack of proper restraints for the subject made task performance more difficult.

Gurfinkel' recorded a small upward movement of the hand during the first period of decreased weight. It was concluded, however, that any discoordination shown was transient, and that there were no significant disturbances in adequacy of performance in setting a pointer or in the regulation of posture or equilibrium.

Unfortunately, the study of any long-lasting effects on or progressive deterioration of the musculature and psychomotor performance cannot be made without a period of zero-g of much longer duration than has yet been obtained, and this awaits the development of a manned, orbiting laboratory.

Hartman et al. (ref. 52) wrote about an exploratory study of psychomotor performance during and after prolonged water immersion, simulating weightlessness. Measures of vigilance and discriminative reaction time obtained periodically while the subject was immersed indicated a small but significant deterioration; performance on a complex operator task also showed some decrement after the week of immersion. Changes in gross behavior after immersion were readily apparent to the investigators. They conclude that "the psychomotor effectiveness of the astronaut will be maintained at an adequate level during prolonged weightlessness, but that psychomotor behavior will be grossly disrupted upon re-entry," (ref. 52, p. 13). The restricted mobility imposed upon the subject, the use of a single subject, and the uncontrolled influence of motivation upon performance lead one to question the generality of the results.

Physical Limitations of the Environment

The mechanical aspect of the weightless environment which sometimes leads to disconcerting incoordination and ineffective performance is the loss of the attractive force perpendicular to the ground. The absence of gravity results in the loss of traction and makes it possible for the body to move away from and remain free of the surface. Gauer and Haber (ref. 22) recognized some of the problems that could arise in attempting to move one's weightless body or perform useful work and Hertzberg (ref. 55) has analyzed the problem in more detail.

When a person pushes an object on earth his traction against the ground makes him part of the mass of the earth and the object of relatively small mass moves noticeably. In the absence of gravity, the two bodies will move apart in proportion to their mass because of the action and reaction of forces. This loss of traction, which normally closes "force circuits," creates a number of mechanical problems. Walking is a good example.

Walking on earth may be described as falling forward while pushing upward through the longitudinal axis of the body; the forward foot catches the body before we fall too far. Forward momentum is sustained by again pushing upward as the center of mass moves forward of the supporting foot. Simons (ref. 96) has experimentally studied walking under zero-g using magnetic and suction cup shoes on a metal walkway to provide adhesive forces. Problems other than the need for static attachment were revealed, such as difficulty in preventing skating or sliding with the magnetic shoes and in checking the forward momentum of one's body. In later work Velcro material has been used on the soles of shoes as an adhesive substance (ref. 51). Locomotion can be achieved in this manner, but it is inefficient and does not capitalize upon the characteristics of the environment, such as the ease of free-floating from one place to another.

Simons and Gardner (ref. 98) have tested the practicality of transporting a man through longer distances by means of a portable, compressed air propulsion device. Tumbling occurs when the line of thrust does not pass through the body's center of mass and is a serious problem. Types of movement that are desirable and the calculated forces required to achieve them are presented, but not all have been confirmed empirically. Initial efforts do indicate, however, that one may be able to learn to use propulsion devices satisfactorily.

The law of conservation of momentum applies also to the case of the free-floating man attempting to apply torque to a fixed object, as in the use of many common tools. It has been found that under such conditions the muscular effort exerted will rotate the man's body about the point of contact with the fixed object (ref. 79). Dzendolet and Rievley (ref. 17) investigated the torque that a man can exert while on an air-bearing frictionless platform. A turning or tightening task is performed with maximum efficiency, that is with minimum movement of the body, if one positions himself at right angles to the axis of rotation. Although short impulse forces are possible without rigid attachment, a handhold is required to keep a man in position at his work area (ref. 16).

Kama (ref. 51), using an air-bearing table to simulate weightlessness, tested the ability to position "weightless" objects accurately. In this case, there was a greater tendency for subjects to undershoot than to overshoot. It must be remembered that here only the objects were weightless, (i.e., frictionless), while the man was not weightless. The validity of this technique has not yet been demonstrated, leaving the results open to interpretation.

The same device was used to determine ability to discriminate masses of varying sizes (ref. 82). The smallest difference in mass of weightless (frictionless) objects that could be discriminated was over twice that under normal (weight) conditions. This result is subject to the same reservations as mentioned above.

Conclusions

In evaluating the findings of these various experiments or in comparing one experiment with another, we must often rely on the authors' judgments of "successful" or "efficient" performance, for in many cases quantitative comparisons are not made, much less tests of statistical significance. Nevertheless, the conclusion that might be drawn is that a person firmly attached to his work place can carry out many psychomotor tasks with reasonable proficiency, and that practice improves performance. If the problem of inadvertent tumbling can be avoided (ref. 98), it appears that a free-floating man oould perform many tasks adequately.

The success of the many pilots and experimenters who have carried out zero-g missions speaks as favorably in behalf of this conclusion as many of the experiments that have been reported—evidence that should not be overlooked in this area. The pilots have demonstrated a high degree of skill in a very complex visual-motor coordination task while the experimenters have successfully performed a wide variety of tasks in the course of their investigations.

PHYSIOLOGICAL FUNCTIONS

The earth's gravity has a constant influence on our day-to-day lives beyond the perceptual and the motor forms of behavior. It also has had its effects on the more mechanical functions of the body's physiological systems that have evolved under its influence. Lack of gravity has corresponding effects that may more properly be considered physiological than psychological because of the life-maintaining activities of the body that are involved.

Not all of the physiological functions that have been considered by previous writers are, on a logical basis, expected to be impaired by zero gravity. Some have been the subject of investigation only because their vital nature makes evidence of their continued satisfactory function in the space environment important, or because it was hoped that such investigations would help throw light on other aspects of bodily or psychological well-being. Others, particularly the circulatory system, have been the object of serious concern. Even sensory deprivation, a condition of prolonged isolation, has been discussed as a danger in space flight that would be enhanced by absence of accustomed gravitational stimuli (ref. 87).

The fundamental obstacle to physiological research during weightlessness lies in the present difficulty of attaining a zero gravity condition for a sufficient length of time. The comparatively slow adaptation of physiological functions to changed physical conditions is likely to cause contamination of physiological measures when the organism is subjected to rapid transitions, as of acceleration in ballistic trajectories.

Circulation

The most common expectation is that prolonged exposure to weightlessness will reduce the body's capacity to adapt to acceleration stress. The heart and circulatory system are a finely adjusted mechanism capable of regulating output according to physical

requirements and the condition of the system. Under high acceleration, when the demand becomes too great, the heart is unable to work against the increased pressure imposed by acceleration. Under acceleration below 1 g, on the other hand, reduced load upon the heart, lowered blood pressure, and reduction of hydrostatic pressure differences may lower heart activity to an inadequate level for adaptation to acceleration stress (refs. 72, 101), while limited use and low workload, if prolonged, tend to cause atrophy and loss of effectiveness in the musculature (refs. 43, 52).

The seriousness of circulatory failure, should it occur, has occasioned much interest in this area (ref. 7); however, disagreement can be found as to the severity of the predicted effects. Some authors (refs. 85, 110, 114) thought the consequences would be no more serious than with changes in body position under 1 g, which also reduce hemostatic pressure gradients. Yet a person may collapse when a sudden change is made after regulatory mechanisms have adjusted to a new body position—for instance, upon standing up after having lain in bed a long time. If this be the case, no disorders may be observed until the organism has lived for some time in the weightless state and is suddenly placed under the increased load of a positive-g field, short exposure may cause no observable impairment of well-being.

Langer (ref. 62) presented an extreme view with regard to heart failure, feeling that under weightlessness life cannot be maintained longer than minutes. This position has become less tenable since numerous animals have survived rocket flights, and especially since the Soviet dogs, Belka and Strelka, have been recovered alive after over 24 hours in orbit (ref. 115).

Animal Studies of Circulation

The most successful observations of cardiac functions have been made on animals in rocket or missile flight. Burch and Gerathewohl (ref. 7) summarized the findings from most of the known studies. American rockets have carried primates or rodents, while the Soviets have made use of their traditional laboratory animal, the dog. Even so, findings have been similar. No serious disturbances have been observed in any of the animals; however, the data recorded during weightlessness are not clearly free of the residual effects of the high acceleration of lift-off, and the briefer the duration of weightlessness, the more likely is this to be true. Moreover, the records of conscious animals may well reflect "emotional" or startle responses to the strange environmental conditions of noise and vibration as well as weightlessness.

Anesthetized primates in V-2 and Aerobee rockets showed a slight rise in arterial pressure during lift-off, decreasing through free fall until the parachute opened. Pulse rates varied slightly, usually increasing during acceleration and dropping to initial rates during weightlessness (ref. 53).

Both anesthetized and conscious dogs were sent on rocket flights in the USSR (refs. 6, 20, 80). In the case of some conscious animals, pulse rate and blood pressure rose, then fell to original levels during weightlessness; in others, there was no change or arterial pressure fell. Lack of a regular pattern of response was attributed to individual differences and "diversity in force and character of the external stimuli on each separate flight" (ref. 6). The records of anesthetized animals showed less change; during weightlessness, pulse rate lowered and blood pressure did not change. From this fact

also it was concluded that the differing reactions of the conscious animals were responses to various unusual stimuli (ref. 20). Perhaps the most significant finding was a longer-lasting influence of acceleration after the transition to weightlessness. According to Galkin et al. (ref. 20), a consequence of weightlessness was slower recovery from the high blood pressure and pulse rate induced by acceleration. Laika is reported to have undergone a sharp increase in heart rate immediately after launch of Sputnik II, but the return to normal rate took three times as long as in previous experiments on the centrifuge, a difference assumed due to the new experience of weightlessness that followed (ref. 61), or to "changes in the functional state of the subcortical formations which regulate circulation" (ref. 13). This latter statement is somewhat difficult to interpret.

Project Mouse-in-Able revealed a decided difference in the responses of two rodents. One showed an increase in heart rate during acceleration, followed by a sudden drop to initial levels at the onset of weightlessness; the other's heart rate was erratic until exposure to zero g, upon which it suddenly rose before returning to normal (ref. 105).

Individual differences again are evident among three monkey passengers in Jupiter nose cones. A squirrel monkey, Old Reliable, and a rhesus monkey, Able, showed similar sharp, brief increases in heart rate during both lift-off acceleration and entry into weightlessness, followed by a return to usual levels. Another squirrel monkey, Baker who shared the nose cone with Able, reacted erratically, a brief rise being followed by a prolonged fall in heart rate and then variations above and below base line rate. These differences in response cannot be attributed either to species differences or to stimuli peculiar to each flight. During the course of the weightless phase, all three eventually established fairly steady heart rates, with fluctuations thought to be due to various startling events in the flight. Blood pressure and other measures remained normal (refs. 12, 18, 44).

EKG records, when available, in some of the studies, show no significant departure from normal, indicating that cardiac functions, including circulation and arterial pressure, must have been maintained (ref. 7).

Interaction Effects

In all the experiments described, the effects of weightlessness have not been isolated from lingering effects of acceleration or reactions to unfamiliar stimuli other than weightlessness. Yet, they represent a not unrealistic approach to tolerance for actual conditions of space flight, for except for flights of long duration, weightlessness will not be isolated from other conditions.

It is desirable to inquire whether weightlessness and acceleration closely following one another interact to change tolerance to either condition (ref. 106). Von Beckh (ref. 107) carried out this inquiry by subjecting eleven subjects to high g-loads (4 to 6.5 g) before entering or after pulling out of the weightless trajectory. When transition to zero g followed high acceleration, blackout lasted longer than during the control runs (acceleration without weightlessness), and some subjects reported discomfort and pronounced disorientation. Heart rate increased during acceleration and fluctuated after entering weightlessness instead of returning to usual levels as during the control flights. These symptoms the author thought lent themselves to more than one explanation, all of which concern the failure of the one g-adapted cardiac mechanism to adjust immediately to the zero-g state.

Similar symptoms representing lowered tolerance to the conditions occurred when acceleration followed weightlessness of 40 to 60 seconds duration. Subjects experienced more strain and discomfort during post-weightlessness acceleration, and some blacked out at lower g levels than in the control runs.

Stutman and Olson (ref. 104) tried to measure the effect on the heart of reentry to 2 1/2 g after weightlessness. The short duration of weightlessness (about 15 seconds) made it difficult to draw conclusions about this effect. A decided slowing of heart rate during weightlessness was noted, however, as well as a tendency toward peripheral blood pooling that was attributed to reduced cardiac output during weightlessness.

Lomonaco et al. have studied the interaction of high accelerations and weightlessness in an elevator type of facility. In one study, they observed displacement of the electrical axis of the heart during controlled apnea, and in another study they found through x-ray photography displacement of the heart and diaphragm (refs. 67, 68).

The question remains, then, of how well the human body can tolerate high-g loads following extended periods of weightlessness. With the possible exception of Laika, no subjects have been observed after more than a few minutes, and indeed, in the case of humans, only a few seconds (Belka and Strelka are excluded from this discussion, since physiological data have not been reported in the literature). This limitation together with the previously discussed confounding due to "emotional" or startle reactions tends to give doubtful value to any measure of the effects of weightlessness per se on heart and circulatory functions. In this light, von Beckh's experiment demonstrating the interaction of weightlessness and acceleration is of special interest.

Immersion Studies

Studies involving prolonged water immersion have been primarily concerned with the effect upon the body of reduced requirement for muscular activity, similar to that which might be encountered in weightlessness. Graybiel and Clark (ref. 43) studied the effect of a two-week regimen of immersion and bed rest on the circulatory system and skeletal musculature of three subjects. While circulatory adjustment to changes in position was markedly affected, no change in muscular strength was found under the conditions of this study. Subjects were accompanied constantly and provided with numerous diversions in order to avoid changes attributable to sensory deprivation, and gross behavior appeared to be normal. The authors proposed that deterioration in the bone structure may occur under reduced structural load and be much harder to counteract than muscular deterioration.

Graveline, McKenzie, Hartman, and Balke (refs. 40, 41, 53, 75) reported extensive observations from an exploratory study of a single subject who was immersed for seven days. The most significant effect was the general deterioration of the circulatory system's regulatory capacity. During the 30 minutes each day the subject spent out of water for clothing change, observers noted deterioration in strength, coordination, and muscle size as the experiment progressed. Simple performance tests indicated a small increase in response time each day. Several metabolic changes in white blood cell count, urinary nitrogen, blood composition, and immunochemical responses which occurred are not readily explainable. Some of the changes may be consistent with the bone deterioration suspected by Graybiel and Clark. Unlike Graybiel and Clark's subjects, this subject experienced a reduced need for sleep but felt some of the same need for physical anchoring of the body noted in the other study.

These preliminary experiments demonstrated both the advantages and the disadvantages of simulating long-term weightlessness by immersion. It provides the only opportunity for extensive physiological measurement, but the applicability of the findings is difficult to determine at the present stage of development of space vehicles. The decrements found could be, in some degree at least, due to the immobility and passivity of the subject. The monotony of the experience appears detrimental to motivation and mental activity and thus may affect many performance measures. The elimination of psychological stresses as well as physical stresses also tends to foster deterioration of circulatory adaptive mechanisms.

Because of the reduction of stimuli in immersion studies, one might ask how much the condition called sensory deprivation contributed to the results. While, as Schock (ref. 87) notes, zero gravity may produce a state of sensory deprivation, plans for space systems in the present or foreseeable future suggest that the operator will be far from starved for sensory stimulation.

Respiration

No difficulty in respiration seems likely in the weightless state, except for the problem of ventilation. The absence of convection currents due to the absence of gravity could mean that exhaled air would remain in front of the nose and stifle a supply of fresh oxygen (ref. 101). This problem, however, seems to be a question of engineering rather than of physiology.

In most of the previously cited experiments on physiological parameters during rocket flights discussed earlier, respiration also was measured. For the most part, no systematic changes in respiratory rate have been observed that can be considered caused by zero gravity. No other measures, such as volume of air exchanged, have been found in the published reports.

In some cases, respiratory rate rose upon transition to weightlessness, then returned to original levels (refs. 13, 20, 44). In others, either a fall in rate or no significant change is reported (refs. 44, 53, 80). Again, no pattern is found in the diversity of response reported.

As was noted in the discussion of cardiac activity, respiratory rate also was sometimes affected by acceleration preceding weightlessness, obscuring the effects due to zero g. Less change has been observed among anesthetized than conscious animals, in those cases in which a comparison can be made (ref. 20). These facts suggest that the changes that were observed reflect startle reactions, of which changes in heart rate were also a part. Throughout the duration of weightlessness, there was generally a return to usual levels of physiological activity and in no case were serious disturbances observed.

Other Observations

Eating problems have been studied by Ward, Hawkins, and Stallings (ref. 119), and by Finkelstein (ref. 51). Special containers and food preparations are required to convey food to the mouth and assist ingestion, since neither fluids nor solids will remain in an open container, but no problems have occurred in the digestive cycle.

Elimination also creates a problem only in control of the waste products. It is interesting to note that in a study of urination (ref. 120) there sometimes was a marked loss of urgency under weightless conditions, indicating that weight rather than distention of the bladder may be the immediate stimulus.

From the beginning of the study of weightlessness in flight, motion sickness has been a recurring problem (refs. 76, 112), suggesting a potential threat to the well-being of space pilots. For instance, von Beckh (ref. 109), Loftus (ref. 66), and Gerathewohl (ref. 31) report vomiting in from 17 to 29 percent of persons participating in zero-g flights. When nausea is the criterion, about one half become ill. The importance of this rate of incidence can easily be overemphasized, for it is probably a problem specific to the conditions under which research has been conducted. The high accelerations preceding and following the zero-g period, anxiety, and fatigue seem to be the principal causes of the disturbance in those who are susceptible. The occurrence of sickness is rare among those accustomed to high accelerations, such as seasoned pilots, and subjects who are highly interested in the research usually adapt to the environment readily even if at first they experience some discomfort. While the consequences would perhaps be severe if motion sickness should be a genuine problem in space flight, the best solution seems to lie in the selection and training of space travelers.

Schock (ref. 89) made a few measurements of GSR (galvanic skin response) during weightlessness flights. Resistance dropped just before acceleration prior to zero g, rose during the acceleration, dropped on entry to zero g, and returned to normal during the remainder of the maneuver. This response pattern might be expected from a logical analysis of the relative physiological and psychological stress of various portions of the maneuver, but no definite conclusions can be drawn.

Conclusions

The physiological activity that has received the most attention is the circulatory system. Weightlessness itself does not appear to cause any changes in circulation other than slight drops in blood pressure and heart rate. Experimental evidence to date supports the view that the greatest risk of circulatory failure resulting from weightlessness would occur upon reentry to a high-g field, after the muscles and circulatory system have become adjusted to the changed pressure relationships that are due to zero gravity.

Other physiological processes that appear not to be appreciably affected by weightlessness are respiration, eating, and elimination; and motion sickness, a large problem in experimental studies, probably is caused by the unusual conditions incident to the flights.

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This list is not an exhaustive bibliography on zero gravity, but it is, we feel, complete with respect to the known papers relevant to human and animal performance as it has been considered in this report. A few items that were not available to the authors for review are indicated by an asterisk.

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ASD TR 61-166
Aerospace Medical Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.
WEIGHTLESSNESS AND PERFORMANCE A REVIEW OF THE LITERATURE, by Lt. J. P. Loftus and Lois R. Hammer. June 1961.
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The implications of weightlessness as encountered in space flight are discussed, and the known research dealing with the psychological and physiological effects of zero gravity is critically reviewed. Topics are grouped under the headings of orientation, psychomotor performance, and physiological functions,

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